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This paper was written as part of the Research and Assessment Systems for Sustainability Program. The Program seeks to foster the design and evaluation of strategies with which the next generation of national and international global environmental change programs might more effectively integrate and support its research, assessment and decision support activities. In particular, we intend to catalyze and contribute to three interrelated lines of work: 1) broadening the science-defined agenda for studying global environmental change to engage more explicitly the socially defined agenda for sustainable development; 2) deepening a place-based, integrated understanding of social and ecological vulnerability to global change; and 3) exploring the design and management of systems that can better integrate research, assessment and decision support activities on problems of global change and sustainability. The Program seeks to contribute to the evolution of strategies for pursuing these goals through collaboration among a small, international group of scholars and program managers involved in the production, assessment, and application of knowledge relating to global environmental change and development.

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Abstract

The 2001 Summer Study of the Research and Assessment Systems for Sustainability Program was a working session to advance the intellectual agenda of science and technology for sustainability. Discussion focused primarily on issues of vulnerability and resilience, as they provide an exceptionally rich "case study" for exploring the conceptual and design challenges facing efforts to build place-based, integrative systems of research, assessment and decision support that can more effectively address problems arising through the interactions of society and environment. The particular objective of the Summer Study was to make significant progress in addressing the following four related groups of questions: what is the Research and Assessment Systems for Sustainability Program's model of vulnerability/resilience for coupled human-environment systems; how can this model be refined, tested, and applied; how can integrated systems of research, assessment and decision support be designed to enable such work; and what methodological and modeling innovations are needed to facilitate the analysis of such systems and to advance understanding of the nonlinear, multi-scale, rapidly evolving relationships between nature and society that are the focus of sustainability science? This paper reports on the discussion at the Summer Study on these four core sets of questions.

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Introduction

This Summer Study of the Research and Assessment Systems for Sustainability Program ("Sustainability Systems") was a working session to advance the intellectual agenda of science and technology for sustainability. The Summer Study focused on issues of vulnerability and resilience. These are not the only issues of concern for sustainability science or even for the Program (for which see the web sites at http://sustainabilityscience.org and http://sust.harvard.edu respectively). They did, however, provide an exceptionally rich "case study" for exploring the conceptual and design challenges facing efforts to build place-based, integrative systems of research, assessment and decision support that can more effectively address problems arising through the interactions of society and environment.

The Summer Study provided an opportunity for synthesizing and advancing the Program's emerging conceptual framework for integrated, place-based vulnerability research and assessment. The workshop included a cross-examination of the ongoing case studies being performed by our principals to evaluate critically the usefulness of the Program's definitions and concepts. It also allowed us to assess the specific implications of this emerging understanding for design decisions on research, assessment and decision support under consideration in the global environmental change management community.

A number of draft white papers emerging from the Program's first year reported on our progress and preliminary findings. They drew on developments within the Program's research teams, the response of the community to our Friibergh Workshop on Sustainability Science, and the first "Dialogue" sessions with government program managers in the U.S. and European communities.

The particular objective of the Summer Study was to make significant progress in addressing four related groups of questions about vulnerability and resilience. In each case, our goal was to emerge from the Summer Study with both a better understanding of the following questions and a well-articulated view of the next steps needed to advance that understanding further over the coming year.

1. What is the Research and Assessment Systems for Sustainability Program's model of vulnerability/resilience for coupled human-environment systems?

2. How can this model be refined, tested, and applied?

3. How can integrated systems of research, assessment and decision support be designed to enable such work?

4. What methodological and modeling innovations are needed to facilitate the analysis of such systems and to advance understanding of the nonlinear, multi-scale, rapidly evolving relationships between nature and society that are the focus of sustainability science?

The Workshop participants' reports on the discussion at the Summer Study on these four core sets of questions constitute the body of this document. A list of participants is found in Appendix A.

1. What is the Sustainability System Program's model of vulnerability/resilience for coupled human-environment systems?[1]

1.1 The concept

Vulnerability is the degree to which a system or unit is likely to experience harm due to exposure to perturbations or stress. (See Appendix B for a glossary of vulnerability-related terms.) The concept of vulnerability originated in research communities examining risks and hazards, climate impacts, and resilience. The vulnerability concept emerged out of the recognition by these research communities that a focus on perturbations alone (environmental, socioeconomic, or technological) was insufficient for understanding responses of and impacts on systems (social groups, ecosystems, or places) exposed to such perturbations. With the concept of vulnerability, it became clear that the ability of a system to attenuate stresses or cope with consequences through various strategies or mechanisms constituted a key determinant of system response, and ultimately, of system impact. Clearer understanding of coping strategies or mechanisms can thus illuminate who and what are at risk from what, and how specific stresses and perturbations evolve into risks and impacts.

Vulnerability in the human sciences is typically identified in terms of three elements:

- system exposure to crises, stresses, and shocks;
- inadequate system capacities to cope; and
- severe consequences and attendant risks of slow (or poor) system recovery.

This perspective from the human sciences suggests that the most vulnerable individuals, groups, classes, and regions or places (ecosystems per se are not addressed) are those that (1) experience the most exposure to perturbations or stresses, (2) are the most sensitive to perturbations or stresses (i.e., most likely to suffer from exposure), and (3) have the weakest capacity to respond and ability to recover.

1.2 Frameworks applied

Beyond this broad agreement, the human sciences apply to vulnerability various frameworks and causal structures, each of which generates different research questions and methodologies. Extending the vulnerability concept to ecological systems serves to amplify this variation.

At least two primary framing designs for vulnerability are common in the human sciences: risk-hazards (RH) and pressure-and-release (PAR) (Figures 1a and 1b). Each framework is conceptual, and reduced from "models" that attempt both to identify and connect the basic elements involved in producing vulnerability. Those concerned with behavioral or decision-making *resources and opportunities* that can be utilized in response to stresses or perturbations most often use the RH model. Alternatively, those concerned with political or economic structures that *constrain behaviors or restrict opportunities* for response to stresses or perturbations frequently prefer the PAR model.

These frameworks are useful in characterizing "human vulnerability," but they mask the complexity of the components, states, and interactions that enter into a more robust construction of vulnerability, and thus they frequently provide simplistic indices and measures that may be misleading or even incorrect. In particular, these frameworks tend to address single stresses or perturbations on an exposed human system

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[1] This section of the report was prepared by B. L. Turner II, Roger Kasperson, Colin Polsky, Wen-hua Hsieh, Jeanne Kasperson, and Andrew Schiller. Turner, Hsieh, and Schiller are at the Graduate School of Geography, Clark University; Kasperson and Kasperson are at the Stockholm Environment Institute; Polsky is at the Belfer Center for Science and International Affairs, Kennedy School of Government, Harvard University.

(group or place), and they pay inadequate attention to the full range of conditions that may render the system sensitive to perturbations, or permit it to cope with exposures. They accord short shrift to how exposed systems themselves may act to amplify, attenuate, or even create stresses. Moreover, interacting or coupled human and environmental systems receive virtually no attention.

Comparisons of the uses of the term vulnerability in the human-sciences literature illustrate these limitations (Figure 2). Most of the work to date treats, in a static way, a single perturbation on a social receptor (a person, household, village, or society). By contrast, sustainability science[2] calls for exploring different and more inclusive dimensions of vulnerability, including how it emerges and ways to reduce it. These more complex dimensions of vulnerability occupy a space in Figure 2 defined by multiple/sequential perturbations, interacting human-environment systems, and dynamic coping strategies and mechanisms – an area not addressed in the human-sciences literature.

1.3 Proposed framework

The proposed framework addresses the vulnerability of interacting human-environment systems to multiple and synergistic stresses that emanate from within as well as outside of the system (Figure 3). The diagram in Figure 3 depicts such a dynamic system, and illustrates these feedbacks and links to forces and factors that operate both "outside" and "inside" the immediate system. Owing to the figure's complexity, it does not directly illustrate the hierarchical (spatial and temporal) nesting in which the assessed system fits and interacts.

Macroforces – from both broad-scale environmental and human systems within which the local system resides – come together to affect the local system and simultaneously influence the pressures that act upon it. Different pressures across scales come together in various sequences to create unique "bundles" of stress that affect local systems. A major hypothesis holds that when stresses or perturbations emanating from the environment coalesce with those arising from society, significant consequences can result. For example, economic depression reduces society's capability to develop or maintain pre-emptive measures to reduce the impacts of drought, such that the co-occurrence of drought and depression synergistically enlarges the vulnerability of the system.

The risks resulting from such vulnerabilities emerge from multiple sources and at different scales. These risks cascade through interacting human and environmental systems to create adverse consequences. These interacting systems exhibit conditions that make them sensitive or resistant to the level of risk confronting them, and, depending on the degree of sensitivity, prompt the system to activate its coping and response mechanisms. These mechanisms either attempt to alleviate stresses on the system directly through increased pre-emptive measures (e.g., building dikes to keep out floodwaters), or, alternatively, they may feed back into and adjust components of the social and ecological system itself (e.g., state-sponsored monetary safety nets for households, or successional growth in a disturbed forest). Before pre-emptive adjustments are brought into play, the human-environment system and any system adjustments previously made, jointly feed back and change the set of stresses and perturbations to which the system is exposed (e.g., land uses feed back in response to land degradation, land cover adjusts in response to regional climate change, income can be redistributed in response to an expanding underclass).

Stresses or perturbations that exceed a system's ability to cope and respond lead to impacts that can, in turn, affect resources and mechanisms for further coping. When impacts are sufficiently significant, they may trigger more fundamental changes in the system, described as adaptations (e.g., in the face of

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[2] See Kates et al. 2001. "Sustainability Science." *Science* 292:641-2; and National Research Council, Board on Sustainable Development. 1999. "Our Common Journey." Chapter 1 in *Our Common Journey: A Transition Toward Sustainability*. Washington, D.C.: National Academy Press.

reduced precipitation, a human community may shift from a rain-fed cultivation economy to ecotourism; a closed woodland ecosystem may become an open savanna).

Mechanisms or strategies for adaptation are not restricted to the scale of the system. The system may adapt to stresses by feeding back on the macroforces from the broader environment, polity, or economy within which the system resides (e.g., increased CO_2 emissions may alter climate sufficiently to cause local political pressure that triggers changes in national policies, reducing CO_2 output, thereby moderating potentially greater future climate changes).

Key elements of any vulnerability framework and assessment

The proposed framework is complex, yet it provides an overall structure within which various existing conceptual frameworks and models can be better evaluated, and from which the development of improved models and applications can draw for guidance. The framework indicates that any vulnerability assessment should consider the following elements.

1. Identify the coupled human-environment system as the subject of analysis

Foremost, vulnerability analysis seeks to identify who or what is vulnerable, to what, and why. Historically, vulnerability analyses have used only one of two primary units of study: individuals or groups in a particular place and circumstance, or ecosystems/biophysical systems. These foci are termed anthropocentric and ecocentric, respectively. Either approach provides only partial assessment. Inasmuch as human and environmental systems have become coupled and often share the same location (or portions thereof), a more integrated approach is necessary.

2. Assess vulnerability in terms of its place-based characteristics

A principal challenge for vulnerability studies is to identify the general characteristics and processes within specific suites of stresses, to understand and predict better the emergence of vulnerabilities in particular human-environment systems. A central hypothesis is that a better understanding of both the specific and the generic is possible through analysis of coupled human-environment systems anchored in particular places, together with comparisons among the place-based systems.

3. Consistently include key system elements

Vulnerability is linked to a suite of system qualities or elements, each of which must be understood in order to address vulnerability of the system as a whole. These include, at a minimum, measures of exposure, the exposure unit, sensitivity, and coping or response.

4. Incorporate multiple and interacting perturbations

The vulnerability of a system is the product of multiple stresses and perturbations emanating from both human and environmental origins. These perturbations differ in their magnitude, sequencing, pace, and timing, and in the specific combinations of them to which systems will be exposed and will have to respond. Since coalescing stresses can enhance or, alternatively, reduce resulting levels of stress on a system, it is important to consider multiple perturbations and their interactions.

5. Profile differential vulnerability

Vulnerability is an emergent property of human-environment systems, the constituent parts of which vary with the time, place, form, and unit of analysis. All parts of the system need not be equally vulnerable; in fact, they may rarely be so. For this reason, the differential vulnerabilities embedded within a system require careful profiling and assessment.

6. Recognize the potential importance of cross-scale dynamics

Human-environment systems are subject to influences that operate and interact, both spatially and temporally, across a range of nested or overlapping scales. Furthermore, such processes unfold at different paces, magnitudes, and levels of complexity. Certain processes may function at a range of scales, but not necessarily at every scale within this range (e.g., both global and local, but skip regional). Understanding such complexities is important for assessing the implications of processes operating at different scales on human-environment systems.

7. Recognize the role of endogenous perturbations

Perturbations or stresses need not arise externally to the affected system. Processes internal to the system can likewise put pressure on the system (e.g., in an agro-ecosystem, cropping decisions can cause land degradation). Yet to date, most vulnerability analyses have focused on external perturbations, not internal or endogenous, and thus the role of endogenous perturbations, and relationships between them and the systems from which they arise, remain poorly understood.

8. Conceptualize vulnerability as dynamic with feedbacks, spirals, and trajectories

Vulnerability is not a static dimension of a system; it changes in response to the combination of stresses pressing on the system and the changing character of the system itself. These stresses and system changes come together to continually move the system towards increased or decreased vulnerability. Such trajectories of vulnerability frequently derive from system feedbacks, themselves often driven by spirals between human and environmental components of the system. These spirals can reinforce or ameliorate degradation and vulnerability.

9. Incorporate nonlinear and stochastic characteristics and surprise

Nonlinear, random, and unanticipated system changes are both commonplace and significant within interacting human-environment systems. Although the “surprise” that may emerge from these unanticipated events and effects may not be understood in the near term, assessments must be open to surprise scenarios.

10. Identify causal structures

The vulnerability framework presented here is silent on the specific forms of the processes that give rise to vulnerability. These processes include both inter- and intra-component interactions. Collectively, they constitute the *causal structure* of vulnerability, and their identification and analysis are central to assessment.

11. Conduct sensitivity analyses on causal structures and potential stresses

Much testing and affirmation needs to precede the development of causal structures that trace relationships from stressors to resulting risks and damages, and from structural properties of the sociopolitical system to vulnerabilities. Cause-and-effect links through which these structures operate remain speculative or intuitive.

12. Start with outcomes to be avoided and work backwards towards stresses

Addressing the most vulnerable coupled human-environment systems (or their parts) may be enhanced by reversing the traditional assessment order (which customarily has proceeded from perturbation to outcome). By starting with the unwanted outcomes and working back through the causal structures to the stresses and perturbations likely to generate these outcomes, those systems most at risk, and those outcomes to be avoided, become the central focus of the assessment.

2. How can the vulnerability conceptual framework be tested and applied in research, assessment, and support systems projects?[3]

The Sustainability Systems' team explored the "Airlie House Vulnerability Framework" by designing four potential vulnerability case studies – Arctic, Yaqui Valley in Sonora, Mexico, Southern Yucatán Peninsular Region (SYPR) in Mexico, and coastal North Carolina development. The four cases provided a diverse set of socioeconomic and ecological conditions with which to view the conceptualization. The groups were asked to use the "Airlie House Vulnerability Framework" (Figure 3) and the list of required elements.

For each of the case studies, groups of team members asked:

- How would you design or redesign the case study to address more thoroughly the vulnerability concept and framework?
- What are the critical questions that need to be addressed in the case?
- How would the project be done?
- How would complexity (e.g., multiple and interacting stresses, multiple spatial and temporal scales, non-linearities) be dealt with?

All of the case study groups concluded that the Vulnerability Framework was a useful conceptualization for vulnerability studies. In the case of the Arctic and Yucatán case studies, the groups used the framework explicitly, illustrating its usefulness by inserting place-specific information in the framework. In the Yaqui Valley case, which incorporates a number of different sectors, all of which interact, the framework diagram could not be used simply. Rather, the group envisioned a series of "exposure sub-units" linked to each other and affecting each other, all experiencing the same external driving forces. In these, responses by the environment or social systems in one sub-unit could affect responses and vulnerability in another. Thus, the degree to which the vulnerability framework was explicitly applied in the design of the vulnerability study may have been related to the scale and complexity of the study –the more constrained the case, the more easily the framework can be applied.

Despite the fact that the case studies were very diverse in terms of scale and complexity, and the vulnerability issues of concern were likewise very different, there were many clear commonalties that suggest some broadly applicable strategies for the development and design of vulnerability research and assessment projects. All cases explicitly defined the vulnerability unit and identified, at least partially, outcomes to be avoided. In the following paragraphs, we discuss these and other common themes and illustrate with specific examples from the case studies.

2.1 Agenda setting, and identification of vulnerabilities of concern

All of our groups emphasized the importance of close links to and the involvement of the decision making community and all stakeholders. Those linkages need to be made at the beginning of the project, so that the focus of the studies incorporates the concerns of the stakeholder groups involved. Agenda setting depends on the local community ideas and insights, with contributions from the research communities' theoretical and experiential contributions. Project design can be envisioned as an iterative process, with team building and agenda setting occurring initially, inventory, research and/or tool-building activities next (with iterations back to agenda setting as necessary), followed by assessment and vulnerability analysis and ultimately decision making (Figure 4). The sequence is clearly not linear, with feedbacks possible at any point, with an explicit option for adaptive learning.

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[3] This section of the report was prepared by Pamela Matson, Amy Luers, and Kim Bonine at the Department of Geological and Environmental Sciences & the Institute for International Studies, Stanford University.

Although the team did not discuss this explicitly, the need for stakeholder involvement is likely to differ at different points in the process. For example, while the research that is required to develop the knowledge base and tools with which to evaluate vulnerability obviously must be informed by the needs and concerns of the stakeholders, the work itself can be driven by the research community. As the research stage proceeds to the decision making stages, policy makers and stakeholder groups in the exposure-unit take over leadership.

2.2 Attention to scale and identification of "exposure unit"

While vulnerability can be addressed at many scales, from the local, single community scale to the scale of whole regions with multiple smaller sectors and communities within, it is clear from our case study analysis that definition of scale and "exposure unit" at the outset of the project is critical. In the Arctic case, the exposure unit is not all of the Arctic or even the Arctic region in one country, but rather three to five indigenous settlements with common environments and outside stressors. In the Yaqui Valley, the exposure unit is not the agricultural sector or the urban system or the coastal fishing communities, but rather the linked land-coast-sea system. In the Yucatán, the exposure unit is a geographically bounded area of wet-dry forest with small-scale subsistence farming. In the coastal case, the exposure unit is the collection of communities and ecosystems in two counties in North Carolina that face common external stressors. These all represent place-based studies, where the spatial dimensions are defined by the dynamics of interest. In the case of the Yaqui Valley, the scale is large because the various components (sectors and communities) on the landscape are tightly linked through the movement of water, air, and money – vulnerability of one component (e.g., coastal zone or fisheries) is dependent in part on the responses and vulnerability of another component (e.g., the irrigated agriculture sector). As illustrated in Figure 5, social and environmental systems within each sector respond to many different kinds of forcings from outside the region, and response in one sector can influence responses in other sectors. In the other two cases, communities and ecosystems on the landscapes at regional scales are less tightly linked and thus the scale of analysis can be more narrowly defined.

Temporal scale is also a critical aspect of the "exposure unit." Analysis of vulnerability in terms of short-term responses in one sector to hazards like drought or hurricanes may yield very different conclusions than an analysis of short- and long-term responses to such hazards or to sustained stresses.

Attention to scale, and explicit analysis of scale mismatches, are also necessary because of the importance of feedbacks between responses in the exposure unit and institutional responses outside the exposure unit. For example, in the case of the two Mexico sites, national policies on agriculture could have dramatically different effects in different places and on different time scales. In the Yaqui Valley, national agriculture policies that remove subsidies for fertilizers could reduce overuse and loss of fertilizer in the upland agriculture systems, thereby reducing the exposure and vulnerability of coastal ecosystems and fisheries to nutrient over-enrichment. In the Yucatán, the same policies could lead to more rapidly degraded agricultural soils and more extensive invasion of bracken fern, with irreversible impacts on forest resources as well as agricultural productivity.

2.3 Team building

Composition of the research team was also addressed by all the case study groups. As noted earlier, it is critical that the vulnerability questions be framed by the local stakeholder communities along with the research community. Participatory research may also make sense in many cases. In the Yaqui Valley case, for example, participatory research in agricultural systems may be the only effective way to develop acceptable alternatives.

In the research and assessment arenas, one of the most important aspects is the engagement of a truly integrated, interdisciplinary team. Questions must be framed by the team, and the questions will differ depending on the composition of a team. For example, in the Yaqui study, the identification and inclusion of a cultural anthropologist or resource sociologist to work on issues related to indigenous peoples and ejidos would almost certainly change the scope and perhaps broaden the usefulness of the analysis.

An additional critical aspect of team building is engaging the vibrant participants at the local scale. For some, especially the young, developing world scientists, part of the payback may well be the opportunity to be creative, imaginative, on the forefront…and this is made even better by the opportunity to work with really good people from afar. But beyond that, how do we make sure they are rewarded? Funding, publications, and recognition are issues of concern.

As teams are established, there are great opportunities to bring researchers who typically have focused on local-scale environmental, resource, or socioeconomic issues together with researchers who have focused more on global change concerns. In the Yaqui Valley case, one could imagine the integration of many different aspects of the global change community – the Land-Ocean Interactions in the Coastal Zone (LOICZ) community could contribute on the coastal zone issues, the International Global Atmospheric Chemistry (IGAC) community on atmosphere-biosphere interactions and atmospheric chemistry, the Global Change and Terrestrial Ecosystem (GCTE) community on the natural and managed ecosystems, the Land-Use and Land-Cover Change (LUCC) community on land use issues, and the Biospheric Aspects of the Hydrological Cycle (BAHC) community on hydrology and surface water issues.[4] There would be a significant role for climate change and paleo-record researchers as well. In the Arctic case study, an interdisciplinary team of medical researchers, biologists, and economists could work together with global change specialists.

How do we engage a broad community in interdisciplinary place-based research without stifling creativity, and without imposing a northern twist on southern issues, or a temperate zone take on arctic issues? We first need to communicate better what we mean by place-based analysis of vulnerability and sustainability. Stop talking, and start doing. There are several things we can do:

- publish, even though we are a great deal short of the perfect case study;
- acknowledge actions, even if incomplete;
- develop a network – an electronic network that provides an outlet for people trying integrative research to communicate and be acknowledged;
- help develop personal networks – make it possible for people with experience to help others (for example, the collaboration of Pro Habitat from Guadalajara, Mexico with Sustainable Seattle and the International Institute for Sustainable Development (IISD));
- meetings/awards – up the ante for doing really integrative stuff;
- finally, while we (Sustainability Systems Program members) cannot impose an agenda, we can help organize, find funding for, advise, and iterate ideas with a local group, and we can try to find the charismatic leader.

2.4 Flexibility in analytical approaches

There are many analytical approaches that will be useful for vulnerability studies, including scenario building and testing, inverse modeling (from the point of view of outcomes to avoid), experiments on alternatives, and the development of complex or simplified systems models. The selection of the

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[4] LOICZ, IGAC, GCTE, LUCC, and BAHC are all projects of the International Geosphere-Biosphere Programme (IGBP).

approach will vary with complexity of the place and goals and desired outcomes. Flexibility will be needed, as this kind of science is long-term and iterative. There is no one right approach for measurement and modeling in the vulnerability context.

All groups identified scenarios as a useful approach to frame vulnerability questions, and to evaluate alternative responses in the human-environment system. These approaches allow the evaluation of potential exogenous as well as endogenous stressors.

2.5 Training

One goal of such place-based analyses should be the training of new interdisciplinary and disciplinary researchers. In developing regions, this kind of training equates to capacity building, and the result is likely to be researchers who play the most critical roles in research and decision making processes over the long-run. Training is a key part of the long-term approach that needs to be taken in vulnerability studies.

2.6 Funding for integrative research

The cases identified the need to develop pre-proposals and proposals for funding of research and assessment activities, and they highlighted the need for collaborative funding to be established early in the project rather than attempting to bring new support online well into the project. It seems likely that support for such endeavors will come from a new kind of funding approach – traditional disciplinary approaches common to all U.S. agencies will not work. There have been very few successful examples of U.S. agency research programs that have funded interdisciplinary efforts such as will be required for vulnerability studies. NASA’s Land Cover Land Use Change (LCLUC) Program funded both the Yaqui and the Yucatán case studies; it was designed explicitly as an interdisciplinary program but was managed out of one program office. Larger efforts modeled on that may be necessary. Partnerships, among agencies, foundations, NGOs and/or corporations, may also be a useful approach; however, it is critically important that vulnerability projects not be expected to patch together funds from multiple sources but rather move ahead with integrated funding sources.

3. How can integrated systems of research, assessment and decision support effectively be designed to address vulnerability/resilience in human-environment systems?[5]

Effectively linking knowledge and action in response to human-environment interactions has proven to be a chronically difficult undertaking. Increasingly, however, it has become recognized that effective institutional responses to this challenge cannot be met through a traditional “pipeline” view of science advising and technology transfer. This is especially true at a time when there is increasing interest in addressing the local consequences of global change, and the local contributions to global change. Needed instead are dynamic, two-way institutional linkages coupling research, assessment and decision support that is relevant and useful at multiple levels, especially in addressing local and regional circumstances.

At the Sustainability Systems Program retreat at Airlie House, discussions addressed an array of issues to broaden our understanding of the institutional dimensions of research, assessment and decision support

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[5] This section of the report was prepared by David W. Cash, Frank Alcock, William Clark, Robert Corell, and Jill Jäger. Cash, Alcock, Clark, and Corell are all affiliated with the Belfer Center for Science and International Affairs, Kennedy School of Government, Harvard University; Corell is also with the Atmospheric Policy Program, American Meteorological Society; Jaeger is at the International Human Dimensions Programme on Global Environmental Change.

(RADS) systems, especially in the context of addressing issues of place-based vulnerability research and management.

3.1 Strategic design challenges

What do actors designing institutional structures that bring science and technology to bear on sustainability problems need to think hard about? Three fundamental (though not mutually exclusive) institutional challenges face efforts to create effectively functioning research, assessment and decision support systems:

Integrating research, assessment and decision making

Decision making about the complex array of sustainability issues demands a correspondingly complex array of scientific and technical information. The context of addressing *place-based* vulnerabilities embedded in *global* environmental change, however, provides novel and difficult challenges for the integration of research, assessment and decision making in order that useful research and assessment is conducted, packaged and utilized. Inadequately addressing this challenge results in a number of possible pitfalls: research and assessment that answers questions that are not relevant to decision makers; useful information produced that is going unnoticed by decision makers (this is particularly important in the context of multi-level problems in which there is no link between information production at one level and information use at other levels); science being "tainted" by politics; and information produced through research and assessment efforts that is packaged in ways that are not useful to decision makers.

Parts of the international agricultural research and extension system have successfully integrated research, assessment and decision making allowing the setting of relevant research agendas and providing avenues for the dissemination of information and technology that is used on the ground by farmers. In contrast, the Global Biodiversity Assessment inadequately linked research, assessment and decision making, resulting in a scientifically credible report that was used little by the intended audience – negotiators to the Convention on Biodiversity.

Integrating different arena(s) to address problems

Recent development in assessment practice has emphasized the need for greater *integration* in assessment. Each of the cases discussed emphasized the need to integrate different arenas to address complex problems. Four particular dimensions of this challenge include integrating: disciplines, knowledges, issues, and scale.

Disciplines

Integrating disciplines has historically been difficult to achieve, but in the face of complex problems with intertwined biogeophysical and social dimensions the importance of integrating across disciplines is critical. Inadequate interdisciplinarity has historically lead to research and assessment that miss significant components of a problem, lead to too narrow a framing of a problem, or do not adequately capture the dynamic interactions between the bio-geo-physical-social components. In the Yaqui Valley, efforts currently attempt to integrate the work of agronomists, ecologists, hydrologists, and economists to address a range of issues at the nexus of agriculture/water/development/aquaculture/etc. In contrast, the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Review (FAR) had relatively little linkage between natural and social science perspectives resulting in major gaps in understanding feedback dynamics between social and biogeophysical systems.

Knowledges

Increasingly, research and assessment systems attempt to incorporate multiple knowledges (e.g., western, science, formal, informal, indigenous, etc.). Such attempts (e.g., Mackenzie River Basin Study[6]) face challenges in establishing institutional structures that can ensure credibility of information, adequate representation, and the validation of different methodologies.

Multiple issues/stresses (a question of scope)

Understanding place-based vulnerability seems to depend on understanding and addressing links between different issues or stresses (different environment and natural resource issues, and between these issues and social/economic/etc. issues). Natural Resource Districts in Nebraska that have the authority to assess and address all natural resource issues have successfully integrated multiple issues into their information and management regimes, resulting in coordinated management actions. In contrast, Groundwater Management Districts in Kansas that have the authority to address only groundwater issues have often conflicted with surface water regimes, producing counter-productive management actions.

Place-based/large-scale (a question of scale)

Given that our emerging definition of "place-based" casts communities, locales, etc., *as embedded* in larger-scale systems, how institutional structures account for the multi-level nature of environment-human interactions is fundamentally important. The Pacific ENSO Applications Center has explicitly linked place-based analysis with global-scale analysis of the climate system, producing information that is locally useful, yet captures the dynamics of the large-scale system. In contrast, current global climate change modeling efforts (general circulation model (GCM) driven) have not successfully linked global-scale dynamics to local-scale dynamics in a way that is useful (or credible) for sub-national decision makers.

Balancing saliency, credibility, and legitimacy

A third institutional challenge faced by efforts to address vulnerability and resilience is that of balancing saliency, credibility, and legitimacy. Salience, credibility, and legitimacy are important to the effectiveness of a research, assessment and decision support system, because their absence creates barriers that lead actors *not* to use information produced in the system. Information not considered salient (e.g., much of the information in the Global Biodiversity Assessment) even if credible and legitimate, will be ignored as simply not germane to the decisions being made. Information not considered credible (e.g., numerous NGO climate assessments), even if salient, will not be used in reevaluating existing decisions, although it may induce attempts to acquire more information in an effort to determine whether the information is credible or to find other, corresponding information that is. Information not considered legitimate (e.g., model outputs from Canadian and UK climate models in the U.S. National Assessment of Climate Change, attributed by U.S. Senators), even if credible and salient, may be rejected as inappropriate for use in a particular decision.

3.2 Institutional barriers

What gets in the way of addressing the challenges outlined above? Many of the barriers that make addressing the above challenges difficult were institutional "solutions" to pre-existing problems, effectively implemented in a context that is different than the one presently framed by sustainability problems. Essentially the institutional landscape can be characterized as being "locked" into institutional structures to address "old" problems through institutional inertia, existing interests, and conceptual frameworks that are difficult to discard. Overcoming these barriers does not necessarily require

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[6] Cohen, Stewart J. 1997. Executive Summary. In *Mackenzie Basin Impact Study (MBIS): Final Report*, edited by Steward Cohen. Downsview: Environment Canada, Environmental Adaptation Research Group.

abandoning old institutional structures but modifying them to reach a new paradigm of integrated research, assessment, and decision support. Some of these barriers include:

Organization at a single level

For a variety of good reasons, societies (and their associated decision making and information functions) have tended to organize at a single level. Such organization, however, hinders the ability to understand and address cross-scale dynamics, exploit scale-dependent comparative advantages, or coordinate decision making. Such institutional structures also can result in decision making at one level that is unintentionally counter-productive at other levels.

Organizing around a narrow time frame

Again, for a variety of good reasons, societies have tended to organize within a relatively narrow temporal domain. As with multi-level dimensions, such organization impedes the ability of institutions to capture inter-temporal dynamics, intergenerational issues, and cumulative effects. Such institutional structures also can result in decision making at one time period that is unintentionally counter-productive at other time periods.

Single issue organization

Societies have also tended to organize by single issues (e.g., U.S. Department of Agriculture, U.S. Environmental Protection Agency, U.S. Geological Survey, etc.). As with the previous barriers, such institutional organization, while providing a variety of different advantages, constrains the ability of institutions to understand the links between different stresses (and the additive, multiplicative or nonlinear relationships between them) and systematically address them. Such institutional structures also can result in decision making to address one issue that is unintentionally counter-productive for other issues or for the system as a whole.

Inadequate capacity

As was made clear in the discussion of cases, one of the most formidable barriers to effectively meeting the above challenges is the inadequate financial, technical, human, social, and coordinating capacities.

3.3 Hypothesized institutional properties of RADS systems that lead to effectiveness

Ongoing research within Theme 3 of the Sustainability Systems Program and evidence from the presentation of cases at the Airlie meeting suggest several properties of research, assessment and decision support systems that lead to effective information production and use for addressing issues of sustainability:

Networked and distributed systems

Distributed networks can be constructed to address specifically the challenges outlined above of integrating across research to decision making, across disciplines, across multiple issues, and across scale. A system that creates or taps into existing rich connections between many different nodes is better able to share information/technologies/expertise within the system, exploit comparative advantages of activities at different nodes, and hedge against system-wide failure through redundancies. Findings also suggest that, especially for the assessment and management of local issues that are embedded in larger-scale systems, systems that institutionally support integration of information and decision making through iterated, two-way communication between users and producers of information are more effective at producing credible and relevant information. Such communication enables policy-relevant scientific agenda setting and packaging of information in ways that are most useful for decision making. Deliberate attempts to construct systems with rich connectivity are seen in the Consultative Group on International

Agricultural Research (CGIAR) system, the U.S. agricultural extension system, the United Nations Environment Programme's Global Environmental Outlook (GEO) program, the Global Change System for Analysis, Research and Training (START) programs, and the emerging Millennium Ecosystem Assessment.

We also hypothesize that systems that strike a balance between highly centralized and highly autonomous structures are able to capture benefits of both paradigms – efficiencies and standardization associated with centralized structures, and specificity to locale and exploitation of comparative advantages at different levels of more autonomous systems. Such hybrid systems can be thought of as a distributed system in which nodes in a network are linked across levels and responsibilities and authority are allocated throughout the system, with clear institutionalized lines of accountability. See Figure 6 for a schematic diagram of such a system.

Flexibility and adaptiveness

We hypothesize that sustained and adaptive networked relationships between science and decision making and across levels contributes to effectiveness. Long-term institutionalized relationships allow legitimacy and credibility to accrue over time, especially critical in an information/decision system that addresses contested and controversial issues. As noted above, iterative interactions between scientists, decision makers, and stakeholders, which are only possible in the context of long-term relationships, encourage the fine-tuning of research agendas, of the assessment process, and of information products over time, thus increasing the saliency. Moreover, an iterative process is a necessary component of adaptive assessment and management, in which policy experimentation and learning can be attempted and assessment can consciously evolve to address changes in policy, science, and the natural environment. Long-term flexibility in such a system also allows for the possibility of cross-fertilization of issue-areas, and more useful analysis of the interactions between environmental risks. One of the tradeoffs of adaptive (evolving) systems is the lack of stability. Especially as the private sector becomes increasingly engaged, confidence in the stability of regulatory regimes becomes critical for long-term investment strategies in information and environmental technologies.

Participation

We hypothesize that participation decisions are critical in determining saliency, legitimacy, and credibility. Participation in research, assessment and decision support efforts has often been characterized by swings of relatively exclusive participation (for example, blue ribbon panels established to maintain scientific credibility) to relatively inclusive participation (for example, the public hearing and development process of the U.S. Fish and Wildlife Service endangered species management plans to maintain political legitimacy).

As opposed to these kinds of dichotomous choices we suggest that a more nuanced approach is more effective, in that greater resources are devoted to understanding the implications of *who* participates, *when*, and for *what purpose*. For example, we hypothesize that: systems that engage end-users (decision makers) in early stages of problem scoping and agenda setting are better able to create salient outcomes (e.g., farmers in the Great Plains); systems that engage experts from different nodes in the system have greater legitimacy (e.g., IPCC Working Group II, Third Assessment Report); and systems that engage experts in providing peer-review have greater credibility.

Funding mechanisms

This is the arena in which the Program has done the least analysis, but it is clearly one of the most critical areas in addressing the barrier of inadequate capacity. Several hypotheses emerge:

- Short funding cycles for research and assessment projects (2-3 years), as opposed to endowed programs (or "science on retainer" models), limit effectiveness because they decrease the opportunity for learning, adaptiveness, and building sustained networks.
- The incremental benefits of funding will be greatest at the regional aggregator scale (the intermediary between large-scale and small-scale processes), the interdisciplinary scale because of advocacy for the discipline, and the locale-level application where a constituency exists.

3.4 Unaddressed questions

Institutional dimensions of RADS that demand greater attention include:

Implications of different RADS systems for different purposes

What are the institutional challenges for structuring different RADS for different purposes? e.g., as in arriving at international protocol for ozone or persistent organic pollutants (POPs), and/or advising decision making at the field level like the international agriculture research system, and/or advising multi-level regulatory decision making as in the Great Plains.

Private/public interactions

How can the relationship between private and public actors be usefully and effectively structured in a RADS system? In many recent issue areas, private firms are playing increasingly important roles in the production and dissemination of information relevant to sustainability (e.g., pharmaceutical firms and biological resources, private weather forecasting firms, and the insurance industry). As such actors become more important in information systems, how can tensions be resolved between the "public good" nature of information and the incentives created by proprietary information? How can the complementary strengths of private and public sources of information be simultaneously harnessed or integrated?

The meta-level – getting from here to there

As we better understand what components of RADS systems lead to effectiveness, a meta-level question is raised: how can we arrive at such systems? What would be involved in moving from more centralized single-level assessment systems to more distributed cross-scale systems that can effectively study and respond to place-based vulnerabilities? What are the important barriers, opportunities, and pitfalls in such a transformation?

4. What methodological and modeling innovations are needed to facilitate the analysis of such systems and to advance understanding of the nonlinear, multi-scale, rapidly evolving relationships between nature and society that are the focus of sustainability science?[7]

Numerical models of vulnerability for ecosystems are routinely being used, but a consistent methodological strategy is almost non-existent. We propose a scientific method using a combined approach, founded in ecosystem science as well as in the social sciences. On the one hand, we find it necessary to go further than before in harmonizing the numerical models being used for the biological and physical assessment of ecosystem change. This includes new ways to devise *multiple* scenarios of "plausible futures," from which one can actually map ecosystem functional aspects that are at risk under a

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[7] This section of the report was prepared by Wolfgang Cramer of the Potsdam Institute for Climate Impact Research and Robert W. Corell of the Belfer Center for Science and International Affairs, Kennedy School of Government & Atmospheric Policy Program, American Meteorological Society.

variety of conditions. On the other hand, it is imperative to involve stakeholders actively in the assessment in a number of ways, e.g. by defining, with them, the list of relevant ecosystem services for the study, as well as relevant indicators and thresholds, and also to ensure their input into the evaluation of scenario calculations. Using such an approach, as outlined in this report, it should be possible to generate coarse-scale, but coherent, continent-wide maps of likely risks in ecosystem function, as defined and perceived by relevant stakeholders. We begin with a discussion of formal methodological approaches, followed by an example method for the assessment of the vulnerability applied to European ecosystems influenced by global environmental change.

4.1 Formal methodologies

Formal methodological approaches that could be considered as suitable candidates for vulnerability, research, analysis, and assessment include:

- complex indicator approaches,
- semi-quantitative typology (degradation syndromes, etc.),
- stochastic economic valuation schemes,
- systems analysis and criticality theory,
- advanced versions of game theory,
- integrated modeling and simulation (emphasizing multi-agent approaches and decision theaters),
- re-analysis of historical records,
- risk and disaster assessment, and
- extreme-value statistics and nonlinear dynamics.

Vulnerability links the natural, economic and social dimensions of global environmental change. Therefore, it was concluded that results can only be achieved in a transdisciplinary context of sustainability science. Discussions suggested that new platforms will be required, such as:

- co-production of knowledge between science and society through policy and research exercises;
- place-based concepts, e.g., construction of regional simulators;
- institutional networks resp. virtual centers for vulnerability research; and
- pre-structuring of the relevant assessment processes.

To expand on the more quantitative aspects of innovative methods and models for vulnerability research, analysis, and assessment the following description was described as a static approach to a formal vulnerability model.

Let E denote a global environmental change-sensitive entity characterized by the properties $e_1, ..., e_N$. Let P denote a global change-related perturbation composed of the disturbance factors $p_1, ..., p_M$. The vulnerability of E with respect to P, $V_E (P)$, is an entity-specific damage function of the entity-specific factors sensitivity, $S_E (P)$, and adaptation, $A_E (P)$. So

$$V_E (P) = f_E (S_E (P), A_E (P)), \qquad (1)$$

where

$$f_E (S_E (P), 0) = S_E (P),$$

i.e,. the sensitivity corresponds to the "naked" vulnerability without any adaptation processes. Equation 1 is fairly general, but we can make a number of simplifying assumptions. The vulnerability may be described, for instance, by some universal function F that relates sensitivity and adaptation:

$$V_E(P) = F(S_E(P), A_E(P)).$$

A plausible further simplification results from factorizing F in the following way:

$$F(S_E(P), A_E(P)) = S_E(P)\, G(A_E(P)),$$

where G is again a universal function.

$S_E(P)$ and $A_E(P)$, in turn, may be expressible in general forms that relate the fundamental set of properties $e_1, ..., e_N$ to the fundamental set of disturbance factors $p_1, ..., p_M$, i.e.,

$$S_E(P) = \sigma(e_1, ..., e_N; p_1, ..., p_M),$$

$$A_E(P) = \alpha(e_1, ..., e_N; p_1, ..., p_M).$$

The set of properties should embrace items like ecological structure, economic value, social balance, technological development, etc.

Under certain circumstances it may even be possible to consider α as independent of the specific type of perturbation, i.e.,

$$\alpha = \alpha(e_1, ..., e_N).$$

Taking into account all these simplifications, one can write

$$V_E(P) = \sigma(e_1, ..., e_N; p_1, ..., p_M)\, G(\alpha(e_1, ..., e_N))$$

$$\equiv \beta(e_1, ..., e_N)\, \sigma(e_1, ..., e_N; p_1, ..., p_M).$$

β represents here a modulation factor that reduces the “naked” vulnerability, thus

$$0 \leq \beta \leq 1.$$

In order to illustrate the formalism, we give the following, absolutely artificial example:

E is a segment of the West-African coastline, characterized by the properties e_1 = exposed monetary value per unit area, e_2 = population density, e_3 = degree of technological development. The climate perturbation P is characterized by p_1 = average rate of sea-level rise, p_2 = relative change in hurricane frequency. If all the simplifying assumptions made above hold, then we obtain

$$V_E(P) = \beta(e_1, e_2, e_3)\, \sigma(e_1, e_2, e_3; p_1, p_2).$$

No-nonsense expressions, for β and σ could be, for instance,

$$\beta(e_1, e_2, e_3) = \frac{C_1}{C_2 + e_1 e_3^2}$$

$$\sigma(e_1, e_2, e_3; p_1, p_2) = \ln^2(e_1 + e_2)\, e^{C_3 p_1 + C_4 p_2}$$

where $C_1, .., C_4$ are appropriate constants.

Thus

$$V_E(P) = \frac{C_1 \ln^2(e_1 + e_2)\, e^{C_3 p_1 + C_4 p_1}}{C_2 + e_1\, e_3^2} \quad .$$

The general approach sketched above is not only static; it is also a *deterministic* one. As a rule, an approach like this one will be needed that is both *dynamical* (reflecting the true time evolution of perturbation, sensitivity, and adaptation) and *statistical* (employing probability distributions in order to calculate expected values).

4.2 A method for the assessment of the vulnerability of European ecosystems to global environmental change

A comprehensive assessment of ecosystem vulnerability might ask for approximate but robust answers to the following major questions:

- What are the main regions or sectors that are *vulnerable* to global change, concerning a range of scenarios for socioeconomic development, land-use change, pollution levels, atmospheric composition, and climate change?
- What are the potential *side effects* of land-use change (e.g., due to changes in agricultural policy) for ecosystem services, water supplies, or biodiversity?
- What are the available *robust* (i.e., low probability of failure) options to alleviate environmental change? For example, what will be the effectiveness of afforestation as a means of sequestering carbon under the terms of the Kyoto Protocol to the United Nations Framework Convention on Climate Change (UNFCCC)?

Although the questions are general and valid answers are likely to be only semi-quantitative or qualitative, the means to address them calls for a high degree of quantification and technical advancement. A method for vulnerability assessment applied to European ecosystems influenced by global environmental change is outlined below.

Selection of ecosystem types and services

Major *ecosystem types* (e.g., for Europe, forests, agricultural ecosystems, grasslands, shrublands, tundra, and wetlands) are considered on a regional scale, using a grid covering the entire continent. The resolution of the grid is data-dependent; approximately 10 km is currently feasible and adequate. Ecosystems are assessed as types in each grid cell, rather than as specific ecosystems in explicit locations. For example, in a given grid cell, the type "dry meadows on south-facing slopes" may be considered, but no specific site with its local peculiarities. This is motivated by the large diversity of ecosystems and ecosystem services in Europe, as well as by the need to provide answers at the continental scale. Including all specific ecosystems would impede the regional scope of the assessment.

Different societal sectors depend and rely on different *ecosystem services*. *Primary services* considered involve the direct use of ecosystems, including, for example, the agricultural and forestry sector. These sectors depend on and change the actual land cover. To these sectors, services are measured as part of some economic balance, usually by producing products, such as food and fibre. These economic sectors are important in almost all European regions but their abundance and character differ greatly. *Other services* include the provision of indirect commercial values (e.g., tourism) or non-commercial values (e.g., biodiversity, slope stability, carbon sequestration, water retention, and supply through the seasons). An indirect "service" is also the absence of uncontrollable wildfires. These services generally need to be managed, are sometimes measured in monetary values, but their actual societal value is often not fully expressed that way. Instead, one must rely on indicators for them, which are determined through an iterative dialogue with stakeholders, focusing on a combination of measures of *ecosystem function* and requirements of *ecosystem characteristics*. A specific case of ecosystem "service" that also will be considered is the public interest in the continued existence of ecosystems due to some intrinsic value, e.g. in a nature reserve.

The ecosystem services we consider for the vulnerability assessment are:

- productivity of natural and managed ecosystems (including crops);
- direct and indirect benefits of ecosystems, such as water resources, habitat and plant species diversity, recreational values, etc., as well as the amount of hazards posed by ecosystems such as fire; and
- stability of ecosystems.

This initial set will be exposed to stakeholders, from all involved sectors, during one or several workshops. The aim is to establish a dialogue which should result in a possible revision of our typology of ecosystem services; improved communication, to stakeholders, of the potential and limitations of quantitative, scenario-based assessments; and a tentative list of suitable indicators for the assessment of significant change in services. Despite the stakeholder interests, an obvious further constraint of the list is the existing technical capacity to make reliable assessments – the resulting list therefore represents a compromise, being achieved through a dialogue between stakeholders and scientists.

Definition of service-specific vulnerability indicators and thresholds

A further objective of the stakeholder dialogue is to identify and define a workable set of indicators that link ecosystem response, ecosystem services, and environmental change. Vulnerability with respect to these ecosystem responses and ecosystem services may thus be estimated using quantitative and semi-quantitative indicators. Table 1 presents a set of possible criteria that can be used for indicator selection.

Table 1. Criteria for indicator selection

Relevance and utility for users	Analytical Soundness	Measurability
Indicators should provide a representative picture of the environmental conditions, pressure on the environment, or society's response	Indicators should be theoretically well founded in technical and scientific terms	Indicators should be readily available or made available at a reasonable cost/benefit ratio
Indicators should be simple, easy to interpret, and able to show trends over time		
Indicators should be responsive to change in the environment and related human activities	Indicators should be based on international standards and international consensus about their validity	Indicators should be adequately documented and of known quality
Indicators should provide a basis for regional comparisons		
Indicators should be either national in scope or applicable to regional environmental issues of national significance	Indicators should lend themselves to be linked with economic models, forecasting, and information systems	Indicators should be updated at regular intervals in accordance with reliable procedures
Indicators should have a target or threshold against which to compare them so that users are able to assess the significance of the values associated with them		

Model-based scenario calculations can be analyzed for geographic indicators, ecosystem indicators, and ecosystem service indicators in relation to all possible forcings. The first involve all grid cells and represent changes in regional patterns (e.g., areal extent and distributions of ecosystems and species). The second involve the ecophysiological responses (e.g., productivity, water retention) and the last ones focus especially on the aspects requested by the stakeholders.

Once the simulated ecosystem response, for a given scenario, leads to local (i.e., grid level) or regional changes in ecosystem behavior and services, its "vulnerability" will be assessed. Critical *thresholds* could be established using socioeconomic methods, if costs of adaptations could be estimated reliably. As an alternative, we propose to assess thresholds through direct assessment by stakeholders, thereby providing a representative and utilitarian definition of vulnerability. Assessment of adaptive potential is then implicit in the process since the vulnerability thresholds are defined upon consideration of secondary effects of possible damages, such as the costs for restoring an ecosystem. These effects are not quantified directly but we are able to appraise them due to the stakeholders expertise and intuition.

Definition of scenarios

Climate models have advanced a long way during recent decades, but their output is still fundamentally controlled by the (uncertain) trends in CO_2 concentration, and their regional performance is still poor. On the other hand, policy requires vulnerability assessments that are not tied to one specific emission level assumption, or to one climate model. For these reasons, *multiple scenarios* should be used as input to the vulnerability analysis and synthesis. Scenarios are now appropriately derived from the Intergovernmental

Panel on Climatic Change (IPCC) emission scenarios (SRES), which include multiple, equally plausible "narratives" that quantify the socioeconomic, technological, and demographic conditions under which the scenarios unfold.

These scenarios can be considered as multiple forcings of societal change. Their application to the impact models results in different land-use patterns (expressed by different maps of ecosystem modification), increasing atmospheric concentrations of CO_2 and other greenhouse gases, annual nitrogen deposition, and the associated regional climate change. Climate can be specified by monthly temperature and rainfall averages and their distributional statistics, using scaled output from many runs of general circulation models (GCMs). Future conditions can then be assessed for several time-slices through the 21st century (e.g., 2010, 2025, 2050, 2100) and, wherever possible, also for the transient evolution of the ecosystem response throughout that century.

At the regional scale, a fully coupled assessment of all environmental forcings, including their internal feedbacks, is currently impossible. Instead, we suggest a factorial consideration of multiple forcings (by SRES-driven CO_2 concentration pathways and the associated climate change realizations from different GCMs, by different nitrogen deposition pathways, and by different evolutions of land use). It is from the analysis of the correspondingly large set of scenario results that robust trends are expected.

Model selection, adaptation and validation

Numerical models need to be adapted, validated and applied to scenarios of changed forcings to quantify possible changes in the selected ecosystem characteristics, their functioning, and their different services. Models exist for the influence of climate and land use on growth and yield of crops in agriculture and forestry; for risk assessment of floods, droughts, forest fires, and storms; for the distributional limits of endangered plants and animals; and for the storage of carbon in ecosystems. These models have limits to their validity, but most have been shown to generate results that may be useful for environmental vulnerability assessment. With improved databases from measurement networks, remote sensing, and experimental sites, the applicability of models can now be tested more rigorously than before.

The application of an ecosystem model to assess changes in carbon storage for a historical time period is demonstrated below. Once such a model reconstruction is considered credible, then a climate/land-use scenario could be used to extrapolate the trends into the future. Figure 7 shows net ecosystem productivity (NEP), i.e., annual change in total carbon, as simulated by the ecosystem process model LPJ (Lund-Potsdam-Jena Dynamic Generic Vegetation Model), averaged over the 20th century for a large part of Europe. Input data are observed monthly climatic trends throughout the century, and the present-day distribution of land use. Broadly speaking, sink areas are mainly located east of 5°E. Regions with maritime climate tend to be carbon sinks while the dry south areas (southern Spain and Portugal) are rather strong sources. A map such as Figure 7, if it were based on a climate and land-use scenario, could serve as direct input into the policy process, since it would depict likely trends in carbon storage as a consequence of European and global trends in the environment.

Evaluation of results, vulnerability maps

Once scenario calculations have been carried out for each (factorial) scenario and each of the selected ecosystem service indicators, a multidimensional analysis of results becomes possible. This analysis should be guided by the initially stated requirement of robust indications of vulnerability. Possible criteria for this would be:

- Perception of stakeholders, as expressed in relation to their threshold definition ("this amount of change matters to me")
- Stability of an observed trend across different forcings ("several scenarios show a similar response")

- Plausibility of the trend (“clearly, this level of change appears to be due to the following factor”)

From this it follows that vulnerability maps should be constructed using an iterative approach, based on the communication with stakeholders. No single presentation of findings is clearly superior to all others, and, conversely, the perception of the trend by a stakeholder is partially influenced by the presentation.

Vulnerability assessment of ecosystem services across a continent is now a real possibility and will be carried out in several projects in the near future. It is important to note that vulnerability is dependent on both perception by and possible adaptation of people. It is therefore necessary that state-of-the-art methods for the assessment of changing ecosystem function are exploited in a procedure that ensures participation by policy makers in business and government and other potential stakeholders. Using such an approach, the potential of a sustainable management of environmental resources, against the backdrop of global change, could become more real than before.

Figures

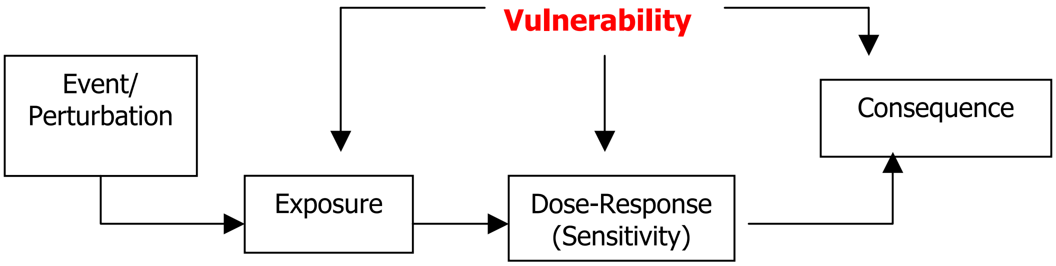

Figure 1a: Risk-hazards framework

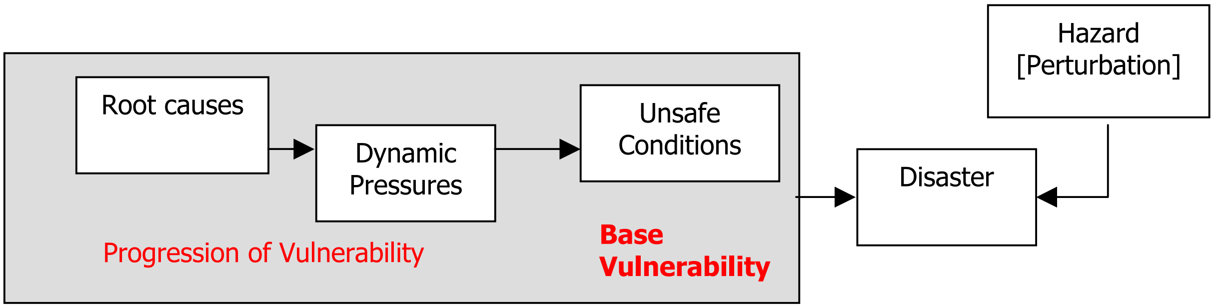

Figure 1b: Pressure-and-release framework

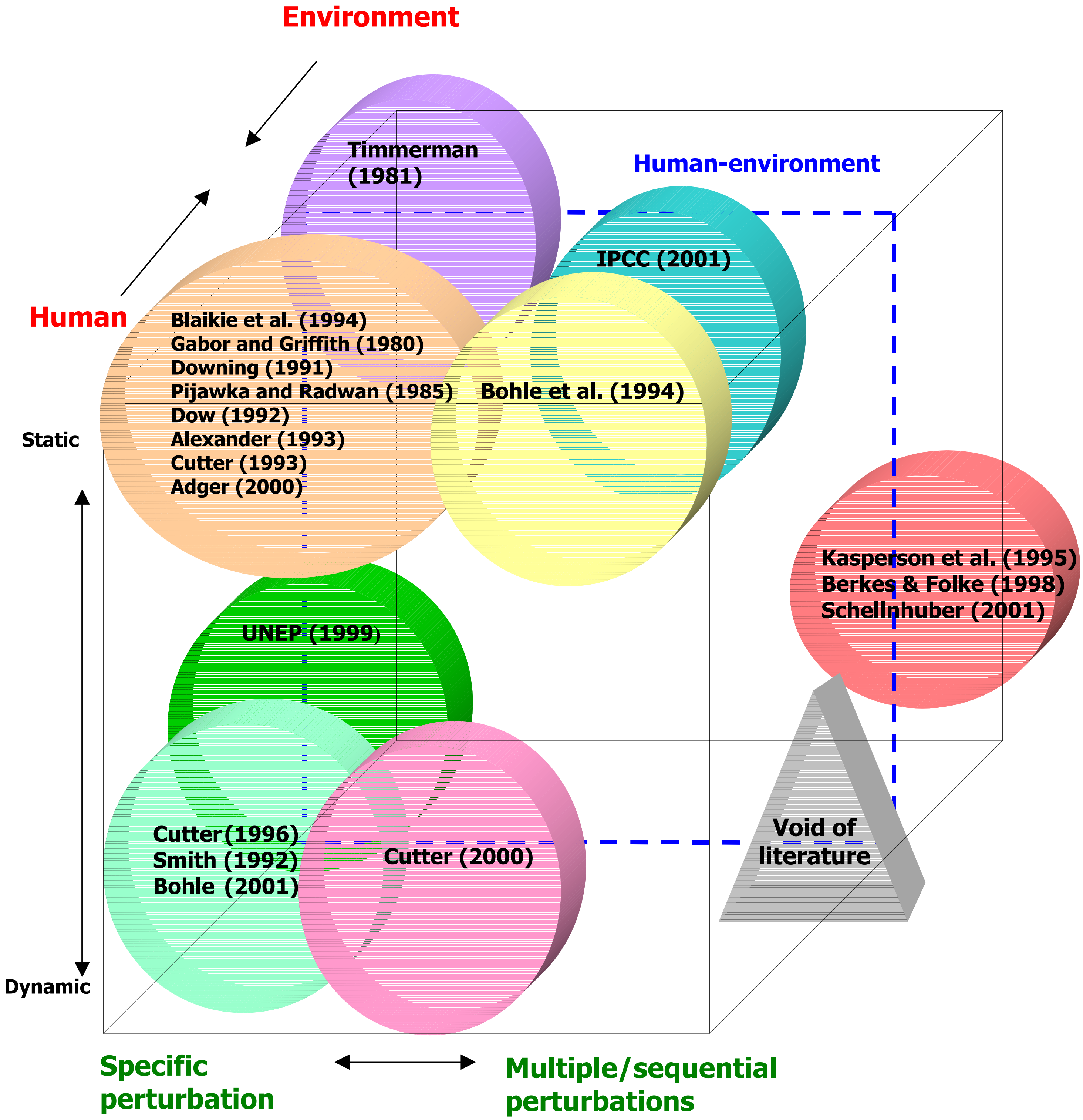

Figure 2: Dimensions of vulnerability research

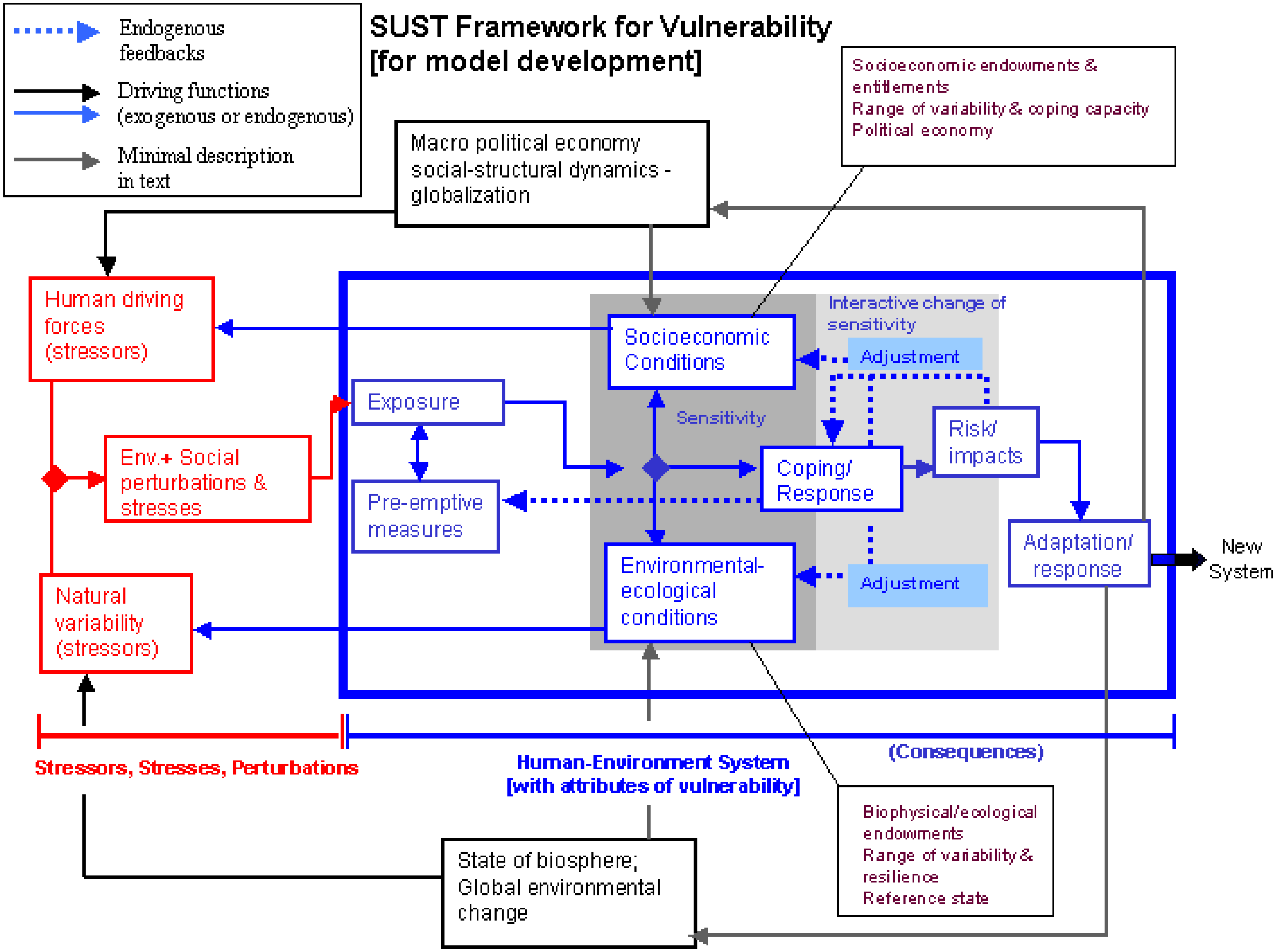

Figure 3: Airlie House vulnerability framework

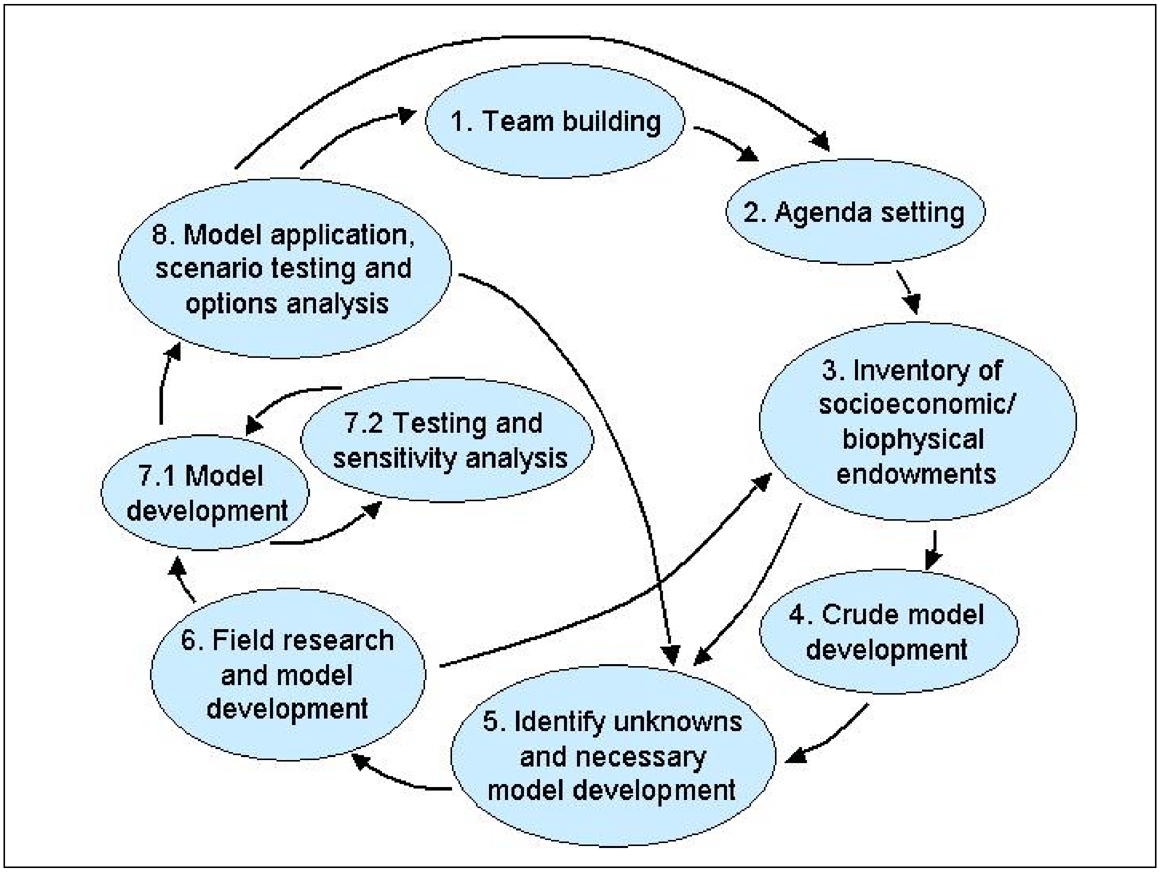

Figure 4: Project design

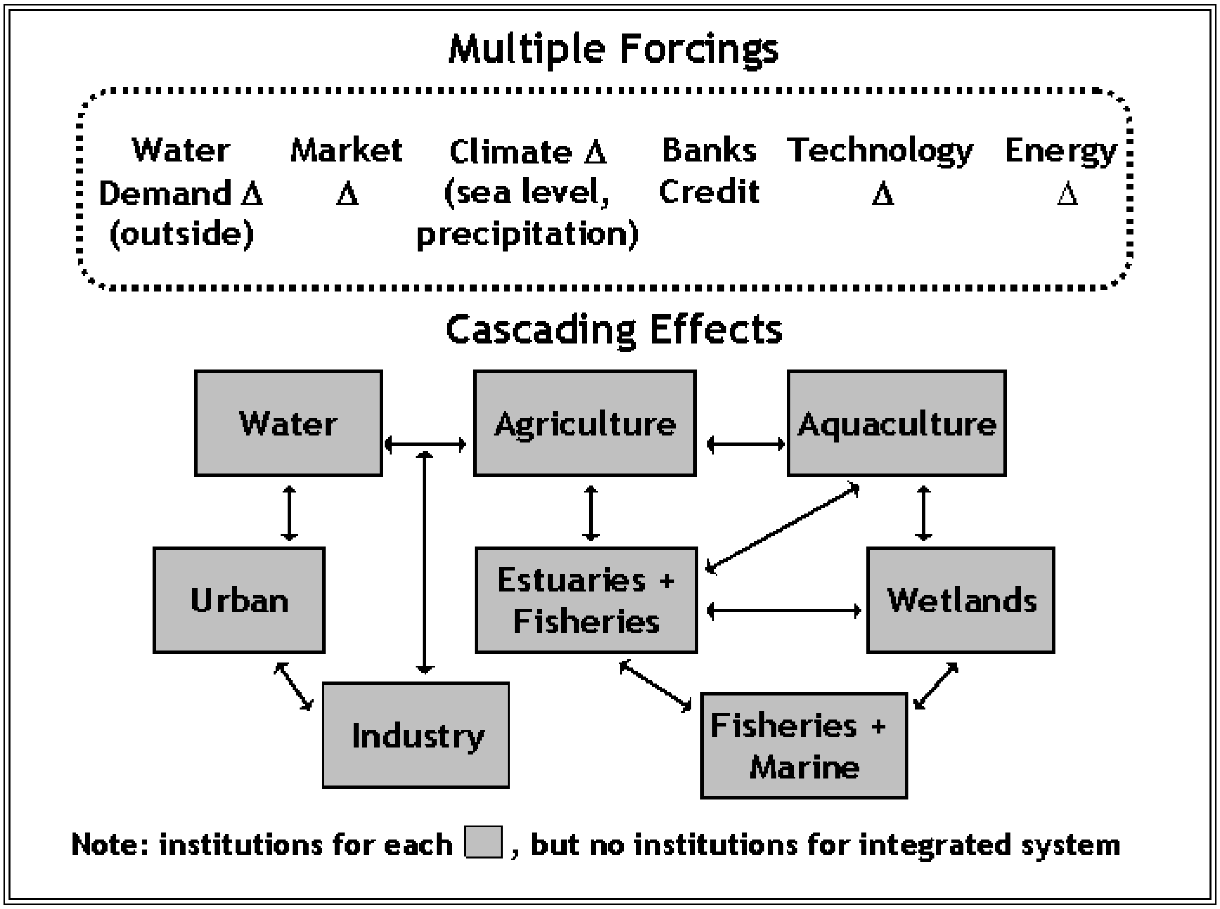

Figure 5: Linkages among sectors of the Yaqui Valley

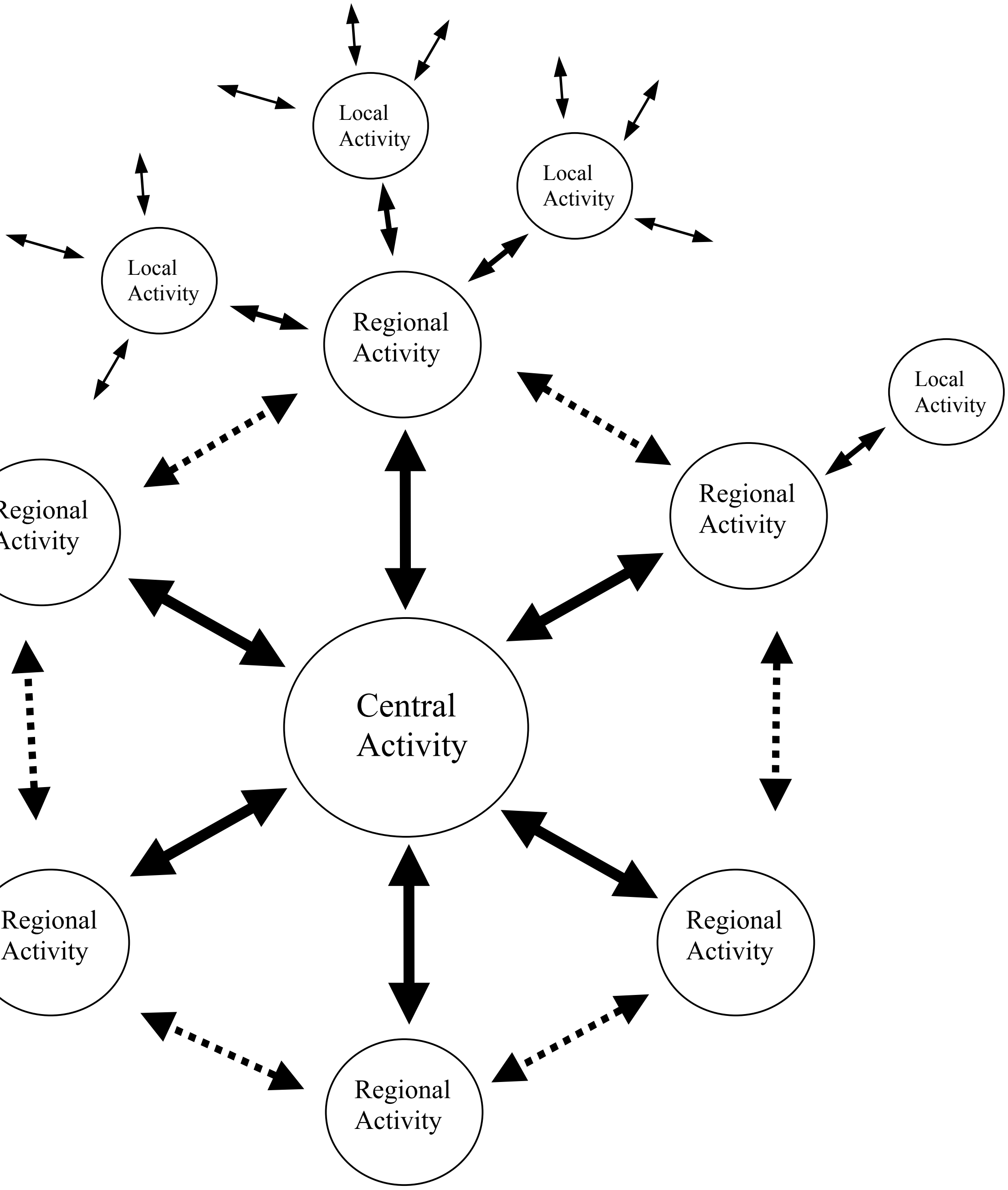

Figure 6: Schematic diagram of a distributed research, assessment and decision support system (adapted from Edward Sarachik, 2001, unpublished figure)

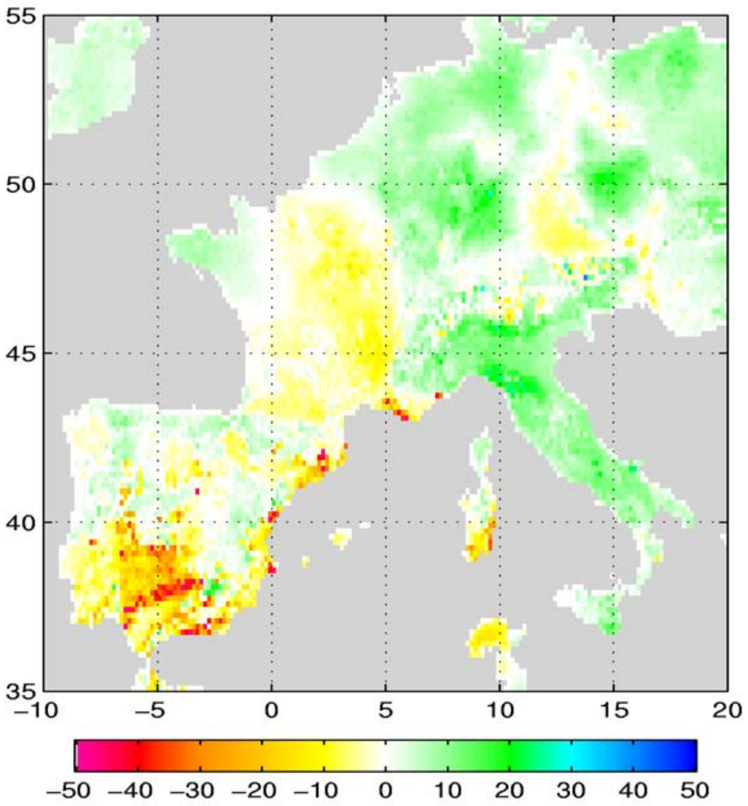

Figure 7: Distribution of net ecosystem productivity (NEP, g C m^{-2} yr^{-1}) averaged over the 20th century, in Central and South-western Europe, simulated by the LPJ ecosystem model

Appendix A: Summer Study Participants

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Appendix B: Glossary of Terms for Vulnerability Framework

Adaptation
A system response to perturbation or stress that is sufficiently fundamental to alter the system itself, usually shifting the system to a new state. Adaptations are commonly but not necessarily long-term in their development and implications. See the distinction below with “adjustment.” Adaptation and adjustment are commonly fused in the literature and do not have standard definitions.

Adjustment
A system response to exposures that does not fundamentally alter the system itself. Adjustments are commonly but not necessarily short-term and involve relatively minor system modifications.

Coping/response
The wide-ranging set of mechanisms used or actions taken (by ecosystems or people) in reaction to threats or impacts. Coping/response includes pre-emptive measures, as well as more reactive adjustments and adaptations.

Coping/response capacity
The <u>potential</u> of a system to reduce impacts from stresses or perturbations, not necessarily the actual coping actions taken in response to a stress. Actual coping can be markedly less than the capacity for coping, depending on system goals and priorities, institutional and informational obstacles, and timely access to coping resources, all of which vary across the human and ecological components of the system. The literature often uses the term “adaptive capacity” in reference to coping/response capacity as defined here.

Coupled human-environment system
A system composed of interacting and partially integrated social and ecological elements and processes, usually coalescing in a particular place.

Endowments
The assets, resources, and qualities, both human and ecological, that determine system capacities for and constraints on responding to stresses and perturbations. These qualities for ecosystems include soil characteristics, species diversity, landscape connectivity, and nutrient cycling, among others; for humans, included are rights, resources (land, skills), information, opportunities, and so forth.

Entitlements
The totality of rights and arrangements (both formal and informal) an individual or group in society can draw upon to establish command over sets of resources and commodities. Entitlements result from endowments, and reside at critical points in the chain of creation or avoidance of social vulnerabilities.

Exposure
The contact between a system, or system component, and a perturbation or stress. Exposure is a function of both the magnitude and scope of the perturbation, and of the system with which it comes into contact (e.g., its location).

Exposure unit
Any system or part of a system that comes into contact with a perturbation or stress. In practice these units include individuals, groups, economic sectors, places, and various parts of ecosystems.

Impact
The consequence(s) of exposure to a perturbation or stress on a system. System consequences can refer either to the *risk* of impact or the actual impact experienced.

Hazard
The threat of a stress or perturbation faced by a system.

Mitigation
A type of coping mechanism utilized or action taken to reduce exposure or sensitivity, or to reduce the harm resulting from such exposure. Mitigation is often used to mean an anticipatory action. Alternatively, mitigation can be used to mean a coping strategy or mechanism (e.g., insurance systems) used after immediate harm or impact has occurred, designed to ameliorate longer-term consequences. Because of these different uses of the term, mitigation is not employed in the current vulnerability framework.

Perturbation
A disturbance to a system resulting from a sudden shock with a magnitude outside the normal range of variability. Perturbations may arise from human driving forces, ecological (natural) events, or combinations of the two. Furthermore, perturbations may arise from within or outside of the exposure unit.

Pre-emptive measure
A type of coping mechanism utilized or action taken (by ecosystems or people) to reduce exposure or sensitivity to a stress. Pre-emptive measures in human systems are anticipatory or preparedness actions. We use pre-emptive measure in place of one of the meanings often ascribed to "mitigation."

Resilience
The ability of a system to absorb perturbations or stresses without changes in its fundamental structure and function that would drive the system into a different state (or extinction).

Risk
The conditional probability of harm attendant on exposure to a perturbation or stress.

Sensitivity
The extent to which a system or its components are likely to experience harm due to an exposure to perturbations or stress.

Stress
Cumulating pressure on a system resulting from processes within the normal range of variability, but which over time may result in disturbances causing the system to adjust, to adapt, or to be harmed.

Stressor
An agent and process – human or ecological (and arising either internally or externally to the system) – that creates stresses or perturbations on an exposed system.

Vulnerability
The degree to which an exposure unit is susceptible to harm due to exposure to a perturbation or stress, and the ability (or lack thereof) of the exposure unit to cope, recover, or fundamentally adapt (become a new system or become extinct).